AD NUMBER
AD828306
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; FEB 1968. Other requests shall be referred to Army Electronics Command, Fort Monmouth, NJ.**
AUTHORITY
ECOM ltr 30 Jul 1971

TECHNICAL REPORT ECOM-01758-8

GUNN EFFECT DEVICES

QUARTERLY REPORT

By

J. BARRERA

FEBRUARY 1968

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

CONTRACT DA 28-043 AMC-01758(E) - ARPA Order No. 692

HEWLETT-PACKARD COMPANY
HEWLETT-PACKARD LABORATORIES
Palo Alto, California

The work prepared under this contract is a part of PROJECT DEFENDER and was made possible by the support of the Advanced Research Projects Agency under Order No. 692, through the U. S. Army Electronics Command.

DISTRIBUTION STATEMENT

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Commanding General, U. S. Army Electronics Command, Fort Monmouth, New Jersey, AMSEL-KL-SM.

Technical Report ECOM-01758-8 FEBRUARY 1968

GUNN EFFECT DEVICES

QUARTERLY REPORT
15 September to 15 December 1967
February 1968

Report No. 8

Contract No. DA 28-043 AMC-01758(E)
ARPA Order No. 692
O/S Task No. 7900.21.243.38.00

Prepared by

J. Barrera

HEWLETT-PACKARD COMPANY
Hewlett-Packard Laboratories
Palo Alto, California

for

U. S. Army Electronics Command, Fort Monmouth, New Jersey

The work prepared under this contract is part of PROJECT DEFENDER and was made possible by the support of the Advanced Research Projects Agency under Order No. 692, through the U. S. Army Electronics Command.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

TRADE NAME DISCLAIMER

The citation of trade names and names of manufacturers in this report is not to be construed as official government indorsement or approval of commercial products or services referenced herein.

Destroy this report when no longer needed. Do not return it to the originator.

ABSTRACT

A development program is to be conducted aimed at the utilization of the Gunn effect for various types of microwave generating devices in the 1 to 50 GHz frequency range. Spectral line width should be less than 10 kHz and operation should be in a single mode. Output power should be at least 25 mw in CW operation and 3W peak in pulsed operation with a conversion efficiency of at least 3%. CW operation should be obtained in ambient temperatures from -25°C to +50°C with a single device.

In compliance with the above objectives, the following work was performed in the last quarter:

Excellent quality solution-grown gallium arsenide is being routinely produced by a transient growth technique. Controlled doping has been achieved with a doping profile of less than 10% over typical device lengths. A steady state growth system is now in operation to produce even better controlled gallium arsenide material with little or no doping profile. Device geometry optimization is continuing with increasing improvement in low sample temperature rise, power output, efficiency, and FM noise. The sample FM noise is consistently low with levels of a few cycles at 10 KHz from the carrier (6 - 13 GHz) in a 200 Hz bandwidth and for relatively low Q's of around 200.

FOREWORD

The work reported on in this report has been authorized by the Contracting Officer, Mr. Edgar D. Fitzgerald, Electronic Components Laboratory, U. S. Army Electronics Command, Ft. Monmouth, New Jersey, under Contract No. DA 28-043 AMC-01758(E) and titled "Gunn Effect Devices." The Project Engineer at the U. S. Army Electronics Command is Mr. Maurice Druesne.

The work has been performed at Hewlett-Packard Laboratories under the supervision of M. M. Atalla. The report has been prepared by J. Barrera. Significant contributions during the report period have been made by N. Mantena, G. W. Mathers, J. Raymond, B. Farrell and T. Fortier. Discussions with M. M. Atalla and C. F. Quate were of great benefit.

TABLE OF CONTENTS

I. GaAs MATERIAL STATUS

I.1 Solution Grown Gallium Arsenide

As indicated in our previous reports, the work at Hewlett-Packard Laboratories on the solution growth technique of gallium arsenide has shown for the first time that such a technique offers the most promising approach to the synthesis of crystals most suitable for bulk oscillation device application. This conslusion is now approaching nearly general acceptance within the industry.

We showed by mid-1967 and reported at the Solid State Device Research Conference[1], that by proper refinement of the solution growth technique, gallium arsenide crystals with a very high degree of purity and essentially theoretical mobilities can be obtained. The consistency between runs was excellent, and material with 10^{13} to mid 10^{4} cm^{-3} carrier density was produced. Mobilities ranged from 6500 to 9500 cm^2/volt-sec at room temperature and around 100,000 or more at liquid nitrogen temperature. Devices fabricated from this high quality material gave the best FM noise performance reported on Gunn effect devices.

Further studies have shown, however, that most crystals, particularly in low carrier concentration range, had a large doping profile along the direction of crystal growth. This was attributed to the <u>transient</u> nature of the growth process and the temperature dependence of the impurity segregation coefficient. This was alleviated during the last quarter by intentionally adding controlled amounts of dopant during growth. The doping levels were

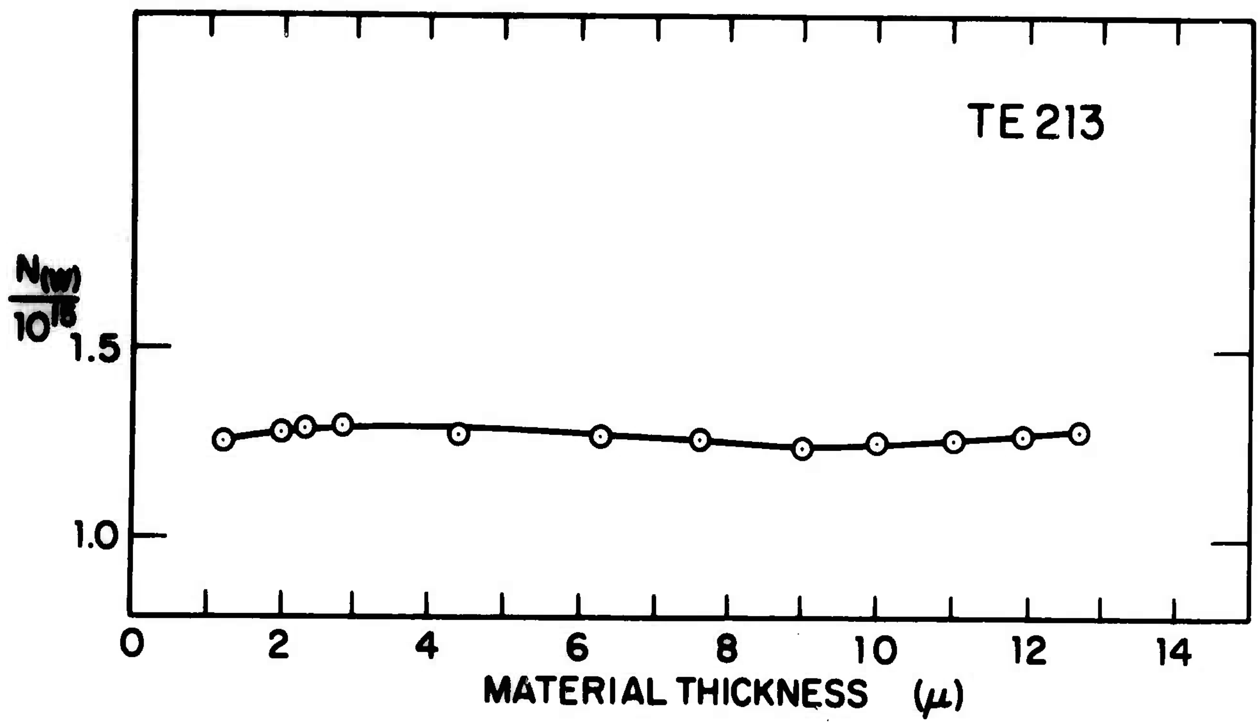
---

1. C. S. Kang and P. E. Greene, "Properties of GaAs Grown by the Liquid Epitaxial Technique and its Application to CW Gunn Oscillators," Session II-2, Santa Barbara, California, 1967.

consistently raised to the mid 10^{14} and low 10^{15} cm^{-3} range. The high crystal quality, as indicated by high mobility, was preserved and the impurity gradient was substantially reduced--particularly at the higher doping levels. Figure 1 shows a plot of total doping profile versus thickness for two typical runs of material--TE 213 and TE 217. For doping levels above about 7×10^{14} cm^{-3} the gradients are less than 10% over device lengths.

In order to completely eliminate the undesirable impurity profile, even at the low carrier concentration, 10^{14} or less, a steady state solution growth setup has been designed and built at our Laboratories. At present all mechanical and electrical systems are working properly, and initial growth studies have begun. In the next six month period, work will be done on optimizing growth conditions for the steady state system with particular emphasis on:

1. Determining the best temperature gradient, ΔT, for quickest growth while maintaining desired crystal quality.
2. Determining the best absolute growth temperature for desired crystal quality.
3. Optimizing temperature cycling of substrate and solution prior to start of growth.
4. Calibrating system with respect to time of growth and desired thickness of epitaxial layer.
5. Determining the best dopant for achieving desired crystal doping level and quality.



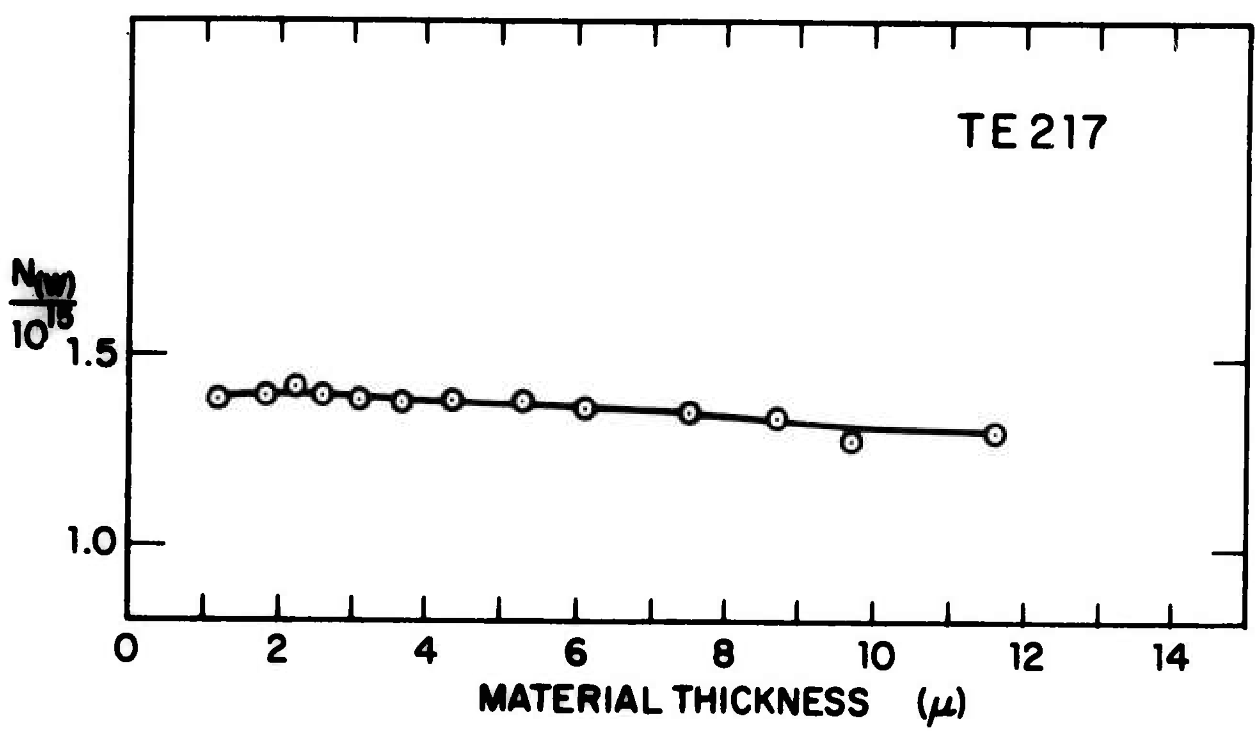


Figure 1. Total doping profile for TE 213 and TE 217 device material.

It is anticipated that the steady state system of solution growth epitaxy will allow growth of high purity GaAs material with little or no doping gradient due to isothermal impurity segregation. Further, it should provide ample versatility regarding thickness control, doping level, and, of course, reproducibility.

I. 2 n^+ Solution Grown GaAs Contacts

One particular item that is receiving and will continue to receive considerable attention is the formation of good ohmic contact to our solution grown GaAs crystals. At present our multi-layer alloyed contact is being used with considerable success. We believe it represents nearly the best achievable by alloying techniques and is adequate for many applications. However, for the ultimate in reproducibility and reliability, we believe that we must incorporate an n^+-GaAs solution growth contact. An effort has already been initiated to achieve this goal and will continue on this program.

The technique involves the growth of thin, highly doped layers of GaAs on both sides of the n-GaAs device material. The growth is out of Ga-In solution saturated with GaAs and dopant. Growth conditions will be optimized with respect to:

1. Initial growth temperature.
2. Cool-down rate.
3. Temperature cycling of solution and substrate prior to growth, and, most importantly,
4. The condition of the n-GaAs surface.

The nature of a properly grown n^+-n junction is such that high field concentrations at the device terminals can be avoided and a more uniform contact provided than from an alloyed contact. It is proposed that separate n^+ solution growths on each side of the active n layer will produce better controlled contact characteristics than use of vapor epitaxy or growth of both n^+ layers simultaneously. Such contacts should give significant improvements in device performance from the standpoints of FM and current noise, power output, and overall device reliability.

II. DEVICE FABRICATION

II.1 Design Considerations

There are several considerations that must be given to the design of a Gunn effect oscillator. In general, a geometrical trade-off is required to meet the requirements of good RF performance and relatively low temperature, long life operation. Our approach has been to tailor the device geometry to minimize the temperature rise while maintaining suitable values for the various RF parameters. Once the characteristics of the device--optimized as above--are known, we can compromise with the geometry to, say, increase power output while keeping the sample temperature rise as low as possible.

We have, as have many other workers, performed a thermal analysis on a given device geometry to obtain the maximum temperature rise at threshold bias conditions. Rather than duplicate the details of the analysis, only the result of the simplest formulation will be given. The power per unit volume into the sample at threshold is taken to be

$$\frac{P_{IN}}{\text{Volume}} = E_{Th}^2 \, \sigma_{(T)} \tag{1}$$

where E_{Th} is the threshold bias field and σ the sample conductivity. The actual power in will be less due to current bendover. The maximum temperature rise, ΔT, above the infinite heat sink temperature, T_o, is given as

$$\Delta T = E_{Th}^2 \, \sigma_{(T)} \left[\frac{r\ell}{K_M} + \frac{\ell^2}{2K_S} + \frac{d\ell}{K_D} \right] \tag{2}$$

or in a more convenient form,

$$\Delta T = E_{Th}^2 \, \sigma_{(T)} \, r^2 \left(\frac{\ell}{r}\right) \left[\frac{1}{K_M} + \left(\frac{\ell}{r}\right)\left(\frac{1}{2K_S} + \frac{1}{\ell}\left(\frac{d}{K_D}\right)\right)\right] \tag{3}$$

This equation is valid for temperature independent thermal conductivities K_M, K_S and K_D (copper heat sink metal, semiconductor and die attach alloy layer, respectively) and for a one-sided infinite heat sink to a device of length ℓ, top contact radius r, and die attach layer thickness d. A plot of ΔT normalized to temperature dependent particle conductivity is given in Figure 2 as a function of device length to top contact radius ratio. The d/K_D parameter corresponds to a 6 μ die attach alloy layer of 0.6 W/°C cm thermal conductivity. The procedure for minimization of temperature rise is obvious--make the devices as short as possible and with as small a contact radius as possible.

To insure good cavity controlled operation, however, a certain minimum $n\ell$ and $f\ell$ product is required. One can thus define a minimum length and doping to cover the operating range of interest and use the contact radius as a parameter to adjust the sample temperature rise, impedance, and overall power output.

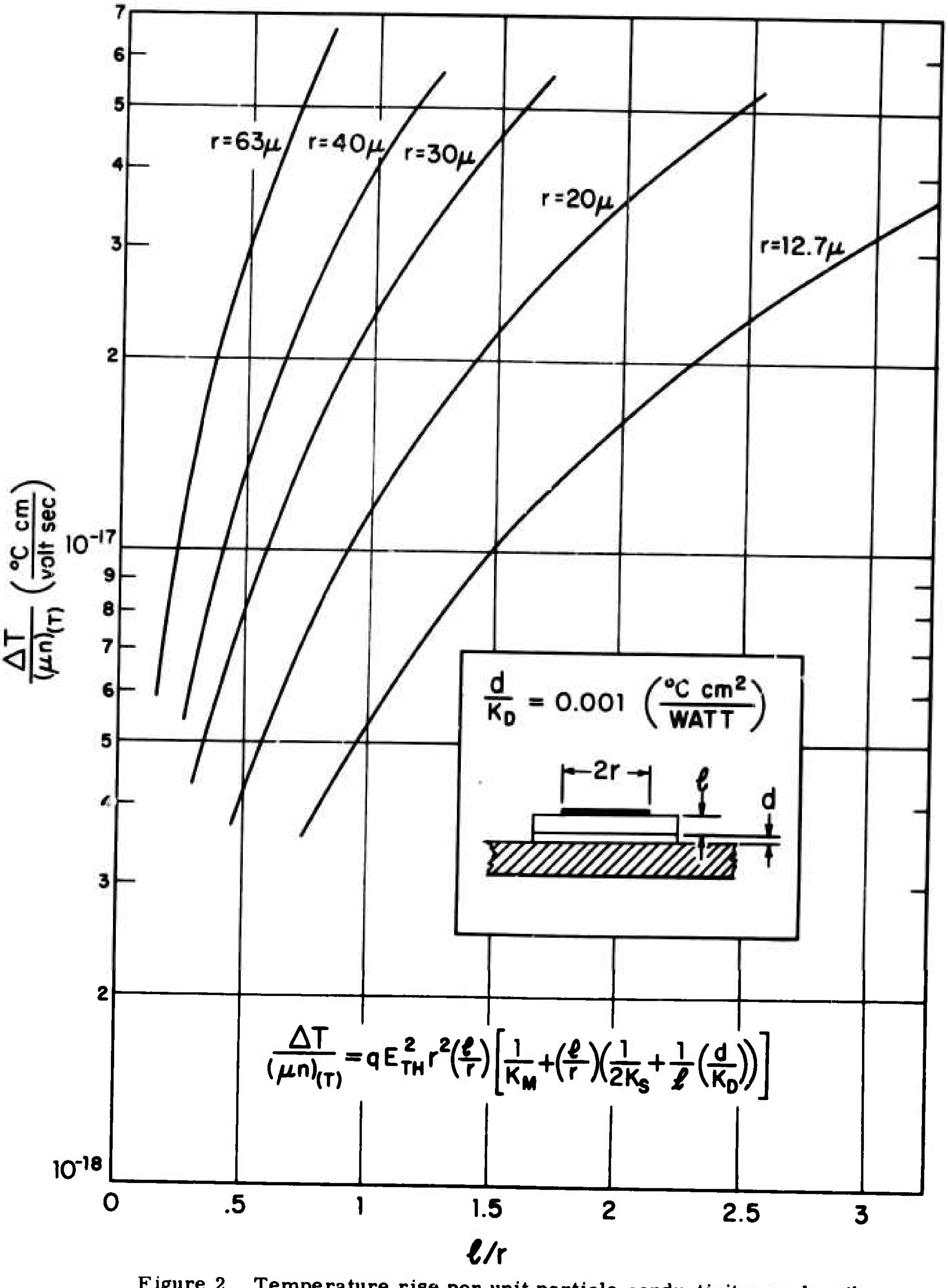


Figure 2. Temperature rise per unit particle conductivity vs. length to contact radius ratio.

II.2 Present Device Geometry

Devices are now being fabricated from 0.3 to 1.6 Ω cm material and are from 9 μ to 20 μ in length. The contact radius can be varied from 30 μ to 50 μ for samples on 7 mil centers. We can thus modify the geometrical and material parameters over the above ranges to optimize the device output characteristics and keep the temperature rise down to about 100°C or less.

III. DEVICE MEASUREMENTS

III. 1 Performance Summary

To ascertain the uniformity and reproducibility of devices, one must fabricate a reasonable number of units per run and subsequently process many different runs. During the last quarter many runs were processed and the latter group--TE 205, 207, 216, 217, 222, and 231--were fabricated from doped solution grown GaAs. The impurity profiles were improved considerably over our undoped material, and the resistivities were comfortably below the 2 to 20 Ωcm level previously obtained.

The consistency both among similar runs and within a run was in general quite good. The efficiencies were from 1.4 to 2.3%, and power outputs were typically from 5 to 12 mw at frequencies around 9 to 12 GHz and from 10 to 30 mw at 6 to 9 GHz. One satisfying feature of essentially all the devices was a consistently low FM noise level. At a frequency of 10 KHz from the carrier, the RMS frequency deviation in a 200 Hz bandwidth ($Q \approx 200$) was typically less than 100 Hz with approximately 50% of the devices having less than 45 Hz. For those devices with the best overall characteristics, the FM noise was extremely low and easily approaching that of good klystrons. In Figures 3 and 4 we show the FM noise spectrum of two TE 231-70 samples (#4 and #6, respectively). These spectra are typical for all twenty TE 231-70 samples mounted and tested to date. Figure 5 shows an actual HP spectrum analyzer display of one of these devices. The line width is easily less than 8 kHz at 3 db down. We feel that the low FM noise is due partly to our efforts in lowering the sample

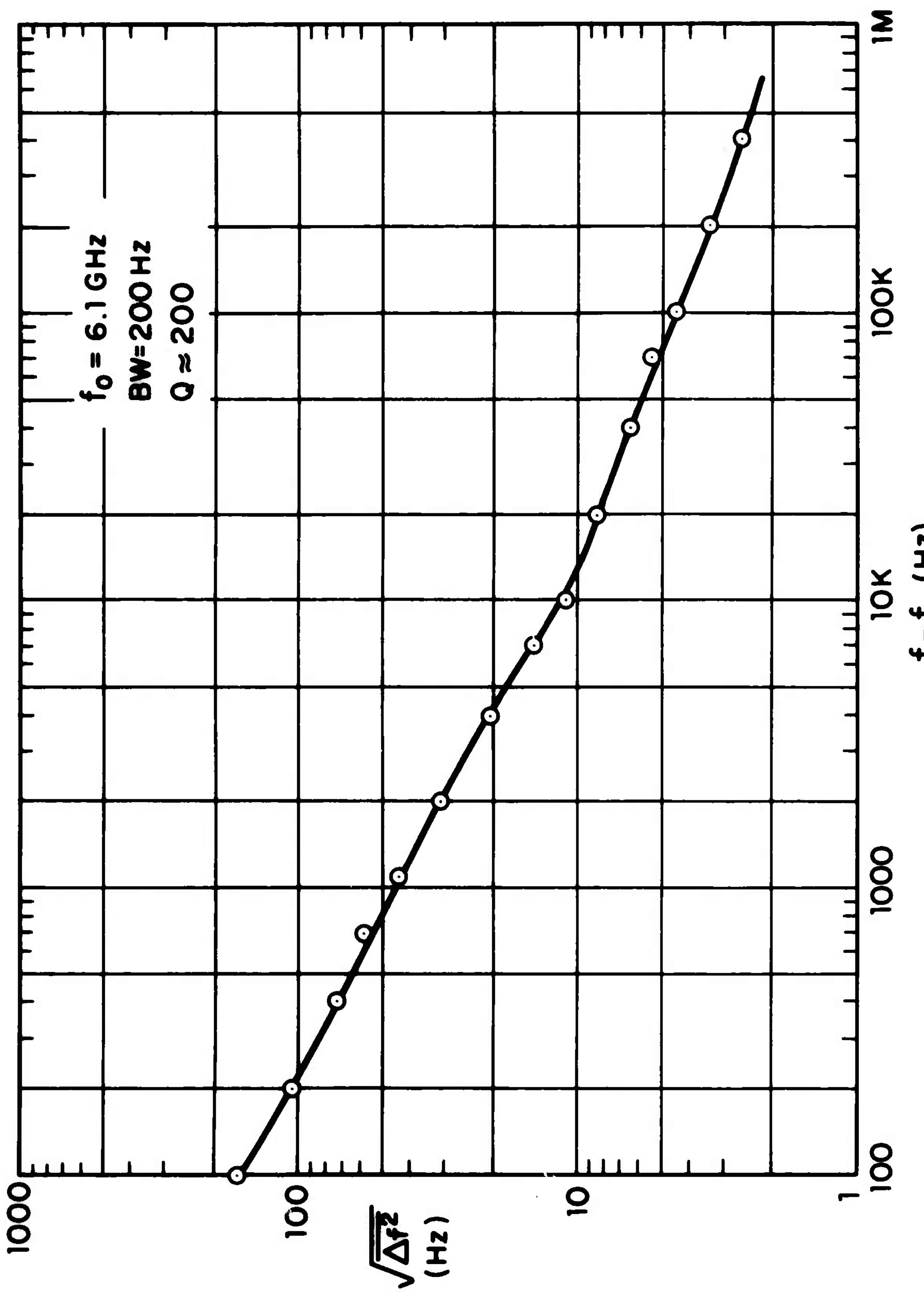


Figure 3. RMS frequency deviation in a 200 Hz bandwidth vs. frequency away from the carrier at 6.1 GHz.

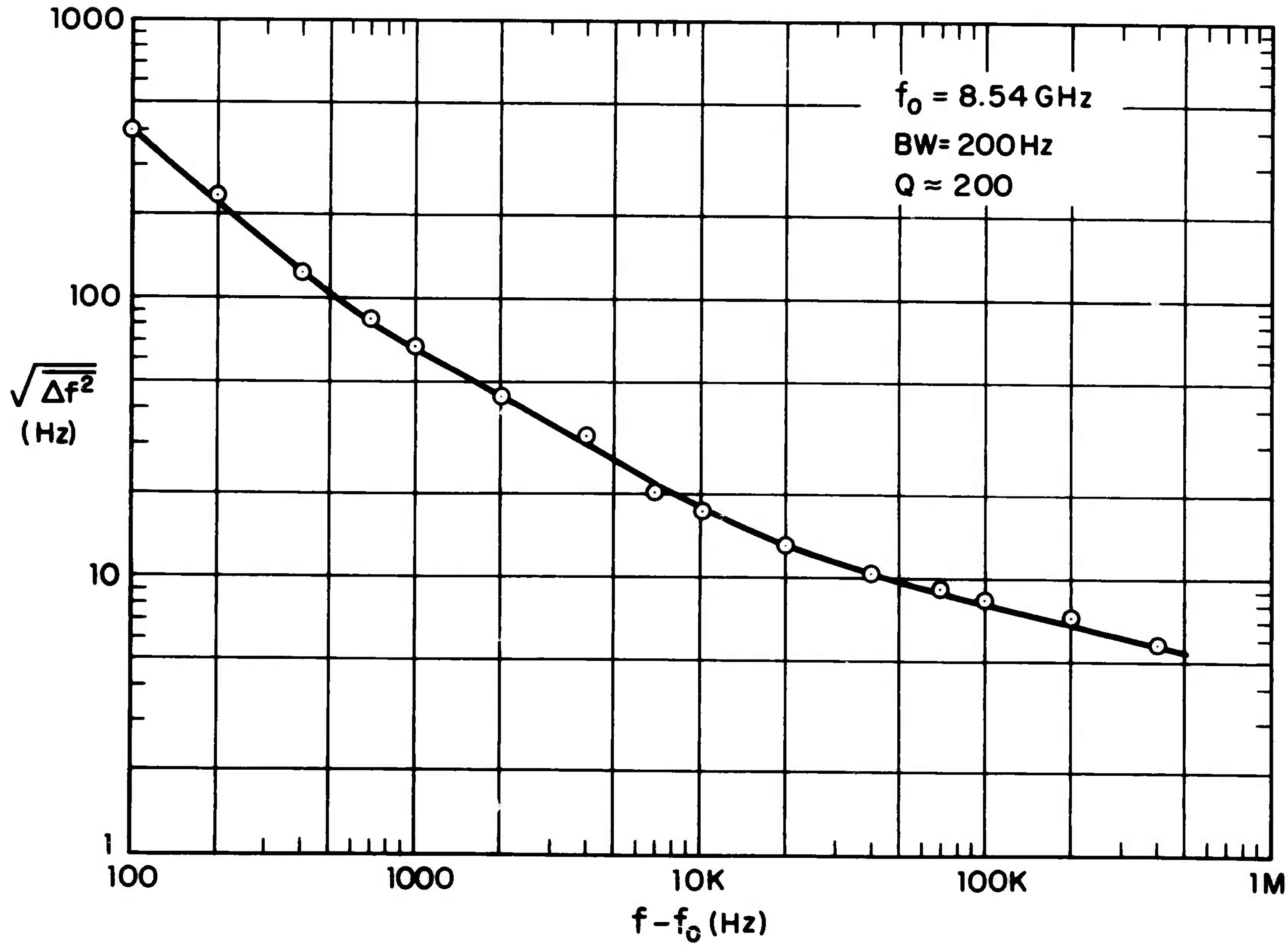


Figure 4. RMS frequency deviation in a 200 Hz bandwidth vs. frequency away from the carrier at 8.45 GHz.

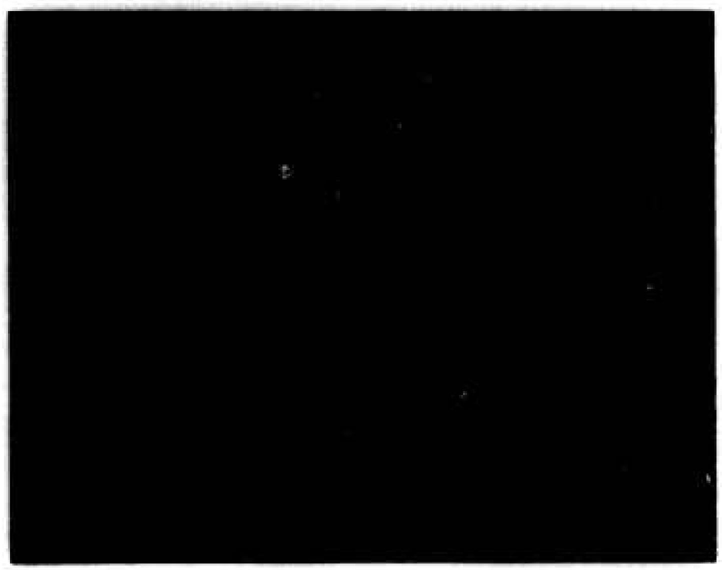


Figure 5. HP spectrum analyzer display of 8.54 GHz oscillator with 30 KHz/cm spectrum width and log attenuation.

excess current noise by surface passivation and special fabricating techniques and partly to the use of good quality GaAs.

The efficiencies are still lower than expected for most of the devices tested. It is believed that the asymmetry of the I-V characteristic with bias polarity, coupled with a still finite doping gradient, is mainly responsible. The increase in efficiencies to over 2% compared to previously reported values is believed due to improvement in both our alloyed contact and doping profile. The degree of asymmetry has been lowered, but with the contact dot (cathode) biased positively there is usually no observed threshold or oscillation on out to avalanche voltages; and the high field current levels are always above those for opposite polarity. The current decrease at threshold for negative bias has been considerably improved, however, with a typical drop of about 20%. Effort is continuing on the improvement of contacting with better efficiency expected as the degree of I-V asymmetry is reduced.

III.2 Power vs. Frequency Measurements

Although there are many things involved in the amount of power one obtains from a given device, there is one particular factor that is somewhat puzzling and is currently being investigated. The problem is the observed fall off of microwave power output with frequency at a rate much greater than f^2 as is expected for a domain mode device. Figure 6 shows a plot of CW output power versus frequency for a typical device at $3.9\ V_{Th}$ and $4.7\ V_{Th}$. The power output is good over an approximate

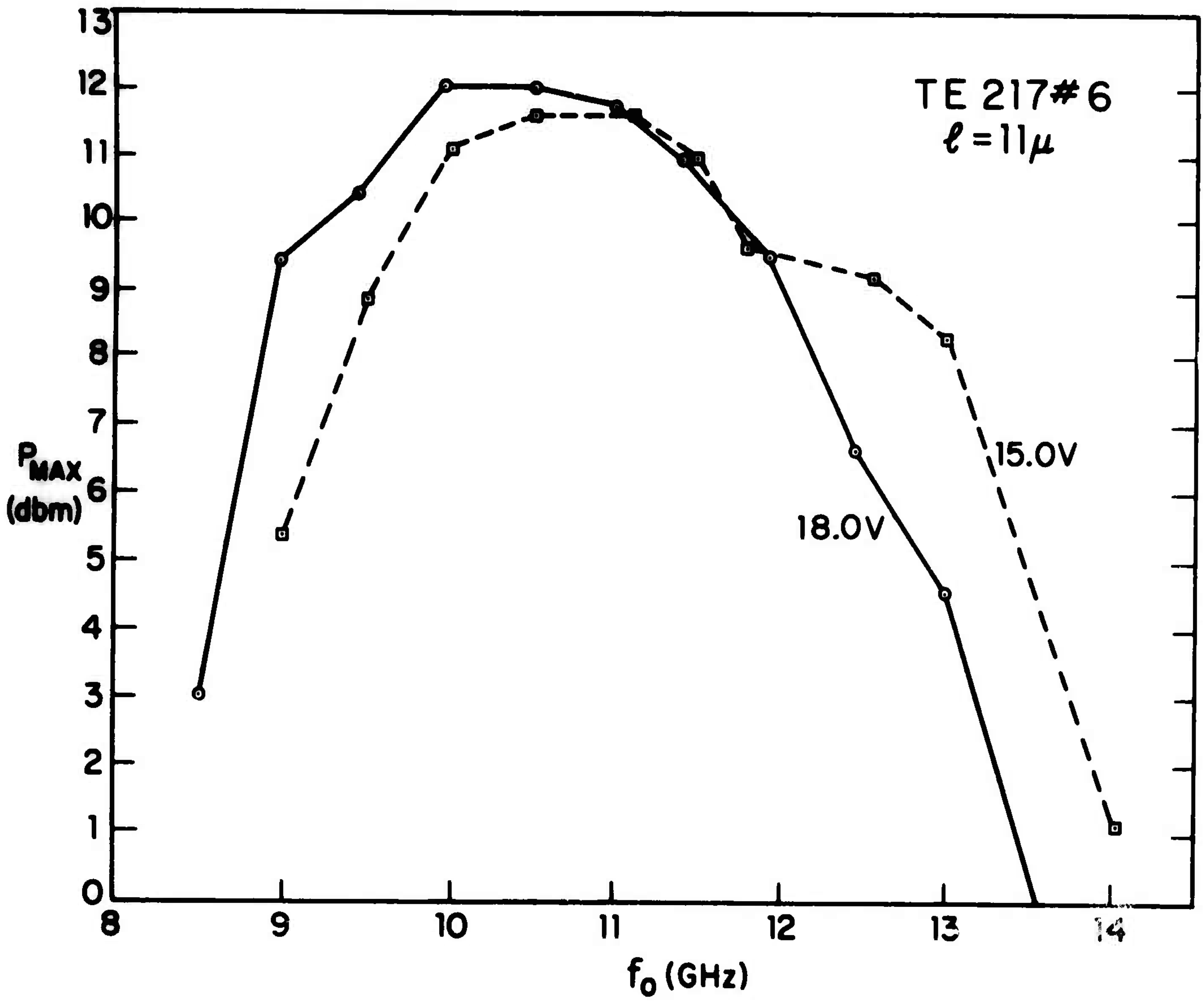


Figure 6. Maximum output power versus frequency.

3 GHz range but deteriorates rapidly outside this range. Another device output is shown in Figure 7 for CW, pulsed and CW-LSA operation with much the same behavior. More of this type of data is presently being taken and studied for some insight into the problem.

III. 3 Measurement of Average Sample Temperature

A scheme has been devised which allows the measurement of an effective temperature of a sample biased slightly below threshold. This method has been used to make an approximate check on calculated temperature rises and thermal resistances. The method involves taking a detailed I-V plot of the device of interest, both CW and pulsed (low duty cycle to prevent heating). The mounted sample is then put into a temperature controlled oven and a constant voltage pulsed bias applied somewhere close to threshold. The corresponding current is then measured as a function of temperature. Figure 8 shows the method in schematic form. Figure 8a is a plot of the necessary I-V data with V_B the pulsed bias point for the temperature measurement and I_{B_1} the current at the reference temperature (usually just RT). Figure 8b shows a plot of the measured current versus temperature. By noticing the temperature at which $I_B(T) = I_{B_2}$ from the CW I-V plot, one has a rather good indicator of the average temperature of the sample under continuous bias conditions.

The thermal resistance of the sample on its mounting heat sink is also obtained by calculating the $I_{B_2} V_B$ product and dividing into the quantity $T_2 - T_1$ thus yielding a "°C/watt" indicator. This scheme, although

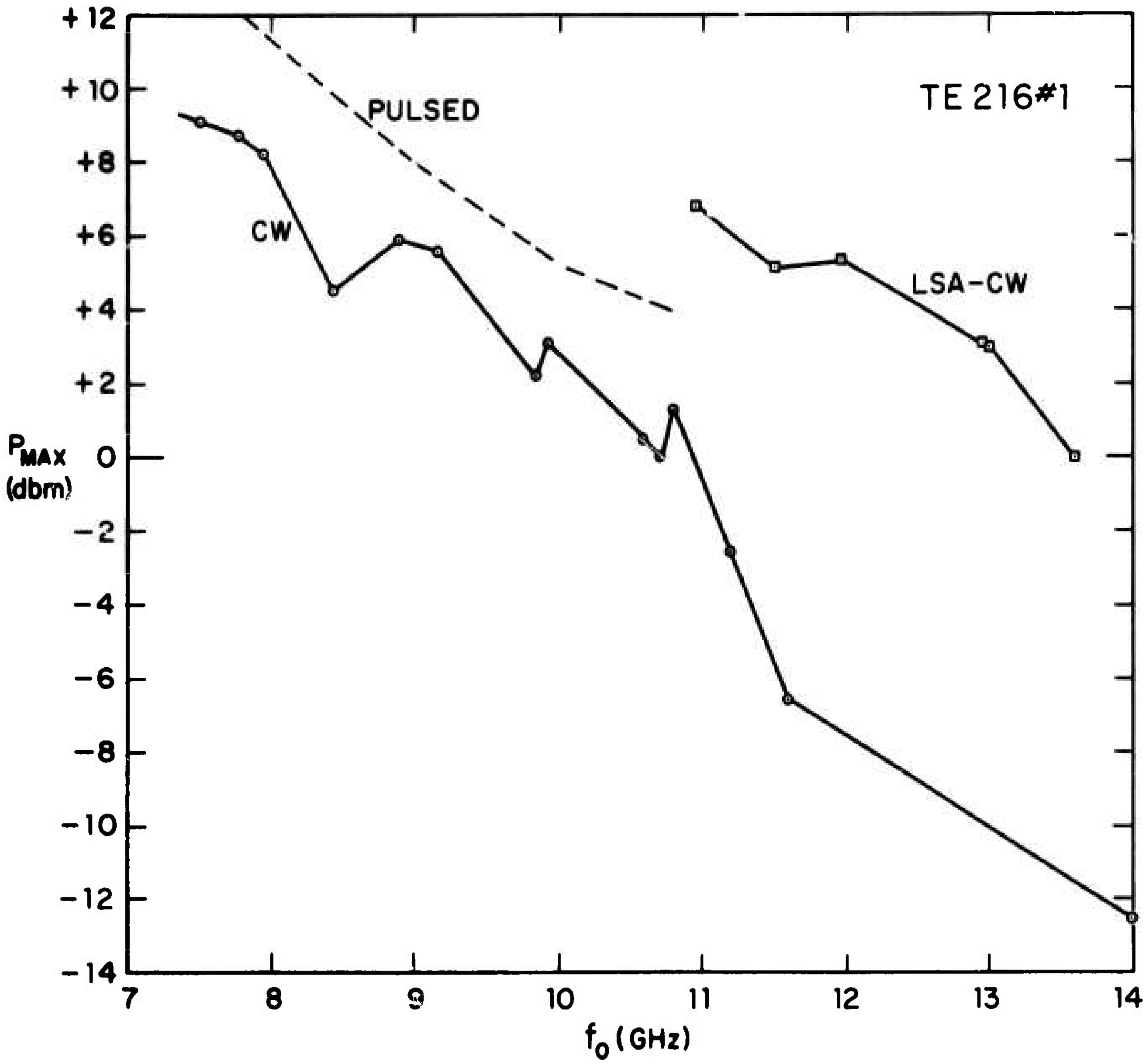


Figure 7. Maximum output power versus frequency.

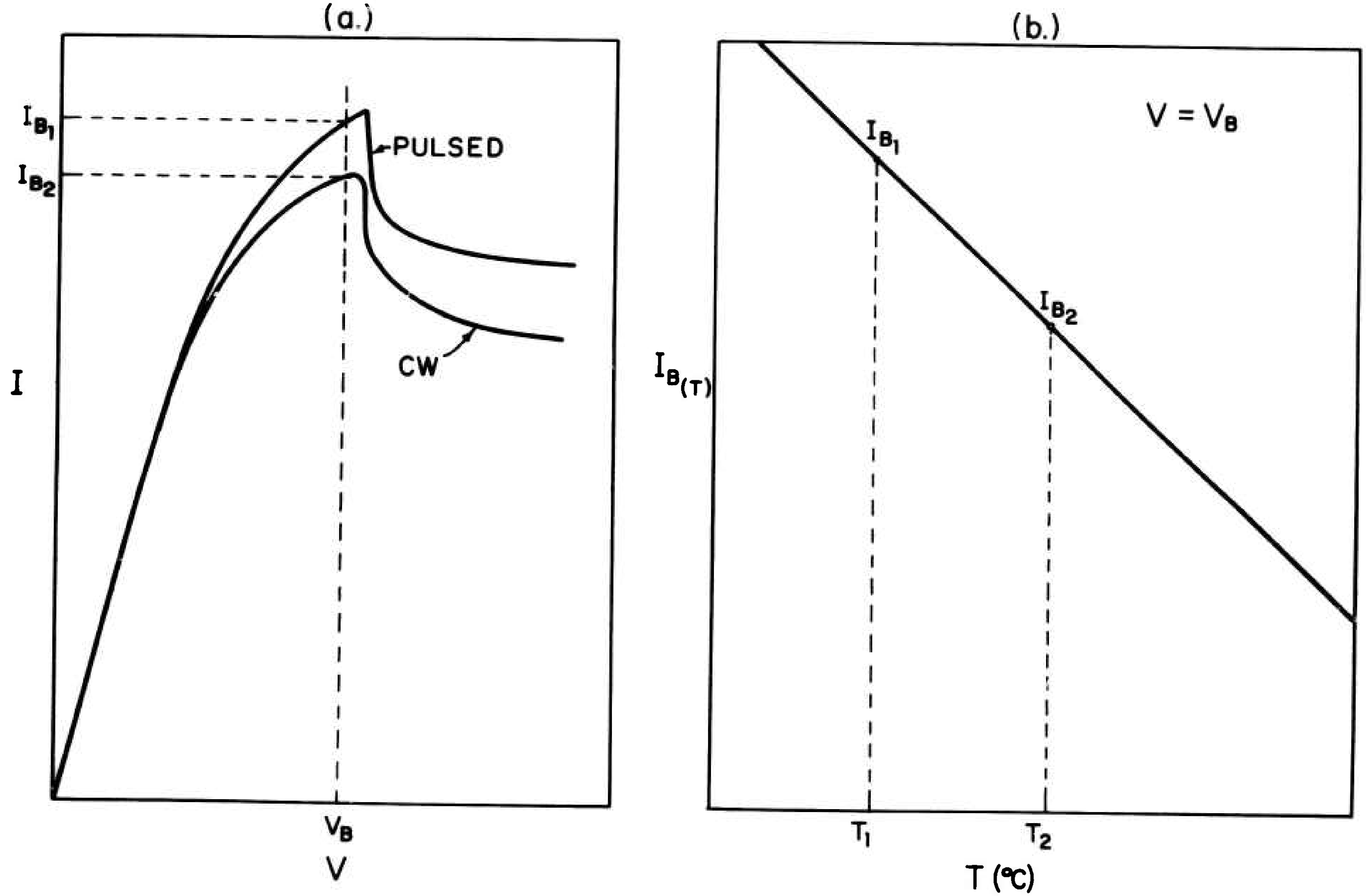


Figure 8. Schematic Plots for Average Sample Temperature Determination.

approximate, is quite simple and does not involve the placement of thermocouples around the sample in a special jig and uses IV data that is taken as a normal procedure.

IV. CONCLUSION

Considerable effort and progress has been made at Hewlett-Packard Laboratories on the development of techniques for the fabrication of oscillator devices. Much attention was given to the many pertinent fabrication details. These included, in particular, surface passivation, die attaching, heat sinking, and overall noise performance. A continuing effort will be made to improve existing techniques to achieve even better control of the above items and to optimize device parameters in general.

The status of GaAs synthesis by liquid epitaxy is such that very reproducible, high quality material is now being routinely produced by the transient growth technique and encouraging results have already been obtained from a new steady state system. The system for producing n^+ solution grown contacts is also being studied, with several successful runs already having been made.

Device fabrication is continuing on a routine basis with stress being put on sample temperature minimization, contact procedures, and sample size to maximize power output, efficiency and low noise, long life operation.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Hewlett-Packard Company 1501 Page Mill Road Palo Alto, California 94304	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Gunn Effect Devices

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Eighth Quarterly Report 15 September to 15 December 1967

5. AUTHOR(S) (First name, middle initial, last name)

Barrera, J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1968	20	0

8a. CONTRACT OR GRANT NO. DA 28-043 AMC-01758(E) b. PROJECT NO. ARPA Order No. 692 c. O/S Task No. 7900.21.243.38.00 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ECOM-01758-8

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Commanding General, U. S. Army Electronics Command, Fort Monmouth, N. J., AMSEL-KL-SM.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Electronics Command Fort Monmouth, New Jersey 07703 AMSEL-KL-SM

13. ABSTRACT

Excellent quality solution-grown gallium arsenide is being routinely produced by a transient growth technique. Controlled doping has been achieved with a doping profile of less than 10% over typical device lengths. A steady state growth system is now in operation to produce even better controlled gallium arsenide material with little or no doping profile. Device geometry optimization is continuing with increasing improvement in low sample temperature rise, power output, efficiency, and FM noise.

Sample FM noise is consistently low with levels of a few cycles at 10 KHz from the carrier (6-13 GHz) in a 200 Hz bandwidth and for relatively low Q's of around 200.

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Microwave Oscillation						
Gunn Effect Devices						
Doping gradient improvement						
Power and efficiency improvement						
Noise performance						

Security Classification